

INSPECTION OF STRYKER ENGINES EVALUATED USING SCPL IN A 20K MILE RAM-D TEST

**INTERIM REPORT
TFLRF No. 452**

by
**Adam C. Brandt
Edwin A. Frame**

**U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute[®] (SwRI[®])
San Antonio, TX**

for
**Allen S. Comfort
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan**

Contract No. W56HZV-09-C-0100 (WD22)

UNCLASSIFIED: Distribution Statement A. Approved for public release

February 2014

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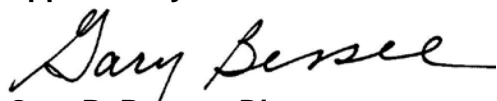
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U.S. Army TARDEC Fuels and Lubricants
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EXECUTIVE SUMMARY

The U.S. Army TARDEC Fuels & Lubricants Technology Team has developed a Single Common Powertrain Lubricant (SCPL) designed to consolidate multiple military lubricant specifications into a single product, or single specification. This report covers the tear down and inspection of two Stryker Caterpillar (CAT) 3126 engines after being evaluated using a candidate SCPL and a baseline MIL-PRF-2104 lubricant, in a 20k mile Reliability, Availability, Maintainability, and Durability (RAM-D) test. Vehicle and engine identification numbers are listed below:

- TEST Stryker, Bumper No. IVC-0482, Engine SN: 1BW02976
- CONTROL Stryker, Bumper No. MEV-013, Engine SN: 1BW03322

After RAM-D testing was completed, the vehicle power packs were crated and shipped to the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) in San Antonio, TX for a full tear down and internal inspection. This inspection included metrology procedures to help quantify wear, ratings of internal deposit formations, and photographs of the “best” and “worst” components removed from the engine for documentation.

Post test inspection and analysis revealed similar overall engine condition for both tested engines. All post test metrology results were within what would be considered normal or expected ranges for used engines in good working condition, and on par with results seen in previous engine dynamometer testing of similar engines completed at the TFLRF in the past. In the ratings section, deposition control for the pistons and valves was found to be acceptable in both engines. The MIL-PRF-2104 used by MEV-013 did show less total accumulation of deposits (i.e. lower ratings) than the SCPL used in IVC-482, but conversely the SCPL showed an advantage in valve deposit control. Despite their minor differences, each oil’s performance was considered sufficient, and results seen from testing would not suggest any significant compatibility problems with either oil.

It is the opinion of TFLRF staff that the SCPL candidate provided comparable wear and deposit control performance to the baseline MIL-PRF-2104 in the Stryker CAT 3126 engines. It is expected that the SCPL can be used as a drop in replacement for the MIL-PRF-2104 without negatively impacting the overall performance of the vehicle and the resulting engine protection.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period September 2012 through December 2013 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Mr. Allen Comfort of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical support staff.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
EXECUTIVE SUMMARY	v
FOREWORD/ACKNOWLEDGMENTS.....	vii
LIST OF TABLES	ix
LIST OF FIGURES	x
ACRONYMS AND ABBREVIATIONS	xi
1.0 BACKGROUND	1
2.0 OBJECTIVE	2
3.0 POWERPACK UNCRATING	3
4.0 RESULTS/DISCUSSION.....	5
4.1 RATINGS	5
4.2 METROLOGY	8
4.3 PHOTOGRAPHS	12
5.0 CONCLUSIONS.....	19
6.0 REFERENCES	20
APPENDIX A: Detailed Metrology Tables.....	A-1
APPENDIX B. Photographs	B-1

LIST OF TABLES

<u>Table</u>	<u>Page</u>
Table 1. Deposit Ratings Results	6
Table 2. Post Test Average Bore Diameter, Skirt Diameter, and Clearance [in]	9
Table 3. Post Test Piston Ring End Gap [in]	10
Table 4. Post Test Valve Stem to Guide Clearance [in]	11
Table 5. Post Test Cam Lobe Variation [μm].....	12
Table A-1. Stryker IVC-482 (TEST) Post Test Cylinder Bore Diameter [in].....	A-1
Table A-2. Stryker MEV-013 (CONTROL) Post Test Cylinder Bore Diameter [in]	A-1
Table A-3. Stryker IVC-482 (TEST) Post Test Valve Train Measurements [in]	A-2
Table A-4. Stryker MEV-013 (CONTROL) Post Test Valve Train Measurements [in].....	A-2

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 1. Stryker MEV-013 Powerpack – 1	3
Figure 2. Stryker MEV-013 Powerpack -2	4
Figure 3. Cylinder Bore “Best”, TEST: #5, CONTROL: #5	13
Figure 4. Cylinder Bore “Worst”, TEST: #5, CONTROL: #2	13
Figure 5. Thrust Side, Piston Skirt “Best”, TEST: #6, CONTROL: #3	14
Figure 6. Thrust Side, Piston Skirt “Worst”, TEST: #1, CONTROL: #4	14
Figure 7. Exhaust and Intake Valves “BEST”, TEST: #3, CONTROL: #1	15
Figure 8. Exhaust and Intake Valves “WORST”, TEST: #2, CONTROL: #5	16
Figure 9. Connecting Rod Bearings (ALL)	17
Figure 10. Crankshaft Main Bearings (ALL)	18
Figure B-1. Piston Crown, “Best”, TEST: #6, CONTROL: #3	B-1
Figure B-2. Piston Crown, “Worst”, TEST: #1, CONTROL: #4	B-1
Figure B-3. Piston Skirt Anti-Thrust, “Best”, TEST: #6, CONTROL: #3	B-2
Figure B-4. Piston Skirt Anti-Thrust, “Worst”, TEST: #1, CONTROL: #4	B-2
Figure B-5. Piston Under Crown, “Best”, TEST: #6, CONTROL: #3	B-3
Figure B-6. Piston Under Crown, “Worst”, TEST: #1, CONTROL: #4	B-3
Figure B-7. Piston Ring Pack, “Best”, Test: #6, Control: #3	B-4
Figure B-8. Piston Ring Pack, “Worst”, Test: #1, Control: #4	B-4
Figure B-9. Thrust Bearing Back, TEST	B-5
Figure B-10. Thrust Bearing Back, CONTROL	B-5
Figure B-11. Thrust Bearing Front, TEST	B-6
Figure B-12. Thrust Bearing Front, CONTROL	B-6

ACRONYMS AND ABBREVIATIONS

ASTM:	American Society of Testing & Materials
CAT:	Caterpillar
FMTV:	Family of Medium Tactical Vehicles
HEUI:	Hydraulically actuated, Electronically controlled, Unit Injector
HP:	Horsepower
ID:	Inside Diameter
in:	Inch
MIL-PRF:	Military Performance
OD:	Outside Diameter
RAM-D:	Reliability, Availability, Maintainability, and Durability
SCPL:	Single Common Powertrain Lubricant
SwRI:	Southwest Research Institute
TARDEC:	Tank Automotive Research Development and Engineering Center
TFLRF:	TARDEC Fuels and Lubricants Research Facility

1.0 BACKGROUND

The U.S. Army TARDEC Fuels & Lubricants Technology Team has developed a Single Common Powertrain Lubricant (SCPL) designed to consolidate multiple military lubricant specifications into a single product, or single specification. The application of the SCPL includes engine lubrication, power shift transmission operation, and limited use in hydraulic systems where MIL-PRF-2104 and MIL-PRF-46167 products are currently used. The SCPL is designed to operate in ambient temperatures ranging from low temperature arctic to high temperature desert conditions, representative of the wide range of potential military operating conditions seen worldwide. The development of the SCPL allows for a single lubricant specification to be universally used in tactical and combat vehicles, despite their seasonal or geographical location, while additionally reducing the logistics burden of the Army's supply chain by requiring only one lubricant to be procured and distributed to its worldwide operations. In addition, technological lubricant advancements of the SCPL allow for improved oil performance and vehicle efficiency over current military specified lubricants [1,2].

This report covers the tear down and inspection of two Caterpillar 3126 engines after being evaluated using a candidate SCPL and a baseline MIL-PRF-2104 lubricant in a 20k mile Reliability, Availability, Maintainability, and Durability (RAM-D) test. The Caterpillar 3126 engine as tested was removed from the IAV Stryker, an 18 ton 8-wheeled armored fighting vehicle and personnel carrier. This medium sized Caterpillar diesel engine shares many similarities to the Caterpillar C7 engine used in all variants of the Family of Medium Tactical Vehicles (FMTV), with the combination of the two engines powering a large portion of the medium tactical wheeled fleet. As a result, these engines are considered "high density" within the Army vehicle fleet. The 3126 and C7 engines are a direct injected, 6 cylinder, turbocharged/aftercooled diesel engine, utilizing a Hydraulically Actuated, Electronically Controlled, Unit Injector (HEUI) type fuel injection system, and range in power output from 300-350hp depending on application. The RAM-D testing completed on the engines reported was coordinated and completed by the U.S. Army TARDEC in Warren MI, with testing administered by the Aberdeen Test Center, Combat Vehicles Division. After testing was completed, the engine and transmission power packs were crated and shipped to the U.S. Army

TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio, TX, for a full tear down and internal inspection. Findings of the engine inspection are covered below. The transmission inspection will be covered in future reporting.

2.0 OBJECTIVE

The objective of this work was to complete a tear down and inspection of two CAT 3126 engines as used in the IAV Stryker. A 20k mile RAM-D test was completed on two vehicles to compare the performance of a newly developed candidate SCPL against currently utilized MIL-PRF-2104 products. The engines were sent to TFLRF after the completed RAM-D testing to be torn down and subjected to a full internal inspection of oil wetted components. This process included metrology procedures to help quantify wear (note, pre test metrology data was not available on these engines, as they were sourced through the military supply system), ratings of internal deposits, and photographs of the “best” and “worst” components to document the condition. The two vehicles were made up of a TEST vehicle utilizing the candidate SCPL, and a CONTROL vehicle utilizing MIL-PRF-2104 products. Vehicle and engine identification numbers are listed below:

- TEST Stryker, Bumper No. IVC-0482, Engine SN: 1BW02976
- CONTROL Stryker, Bumper No. MEV-013, Engine SN: 1BW03322

Results for each engine are outlined in the following sections.

3.0 POWERPACK UNCRATING

The engines were sent to TFLRF in fully assembled powerpack form. This was done as additional work is expected in regards to the transmissions in a future work directive. Once received, the shipping container tops were removed from the powerpack crates, and the container base and pack were moved indoors to facilitate disassembly. Figure 1 and Figure 2 show the powerpack assembly of Stryker MEV-013 (CONTROL) prior to tear down.

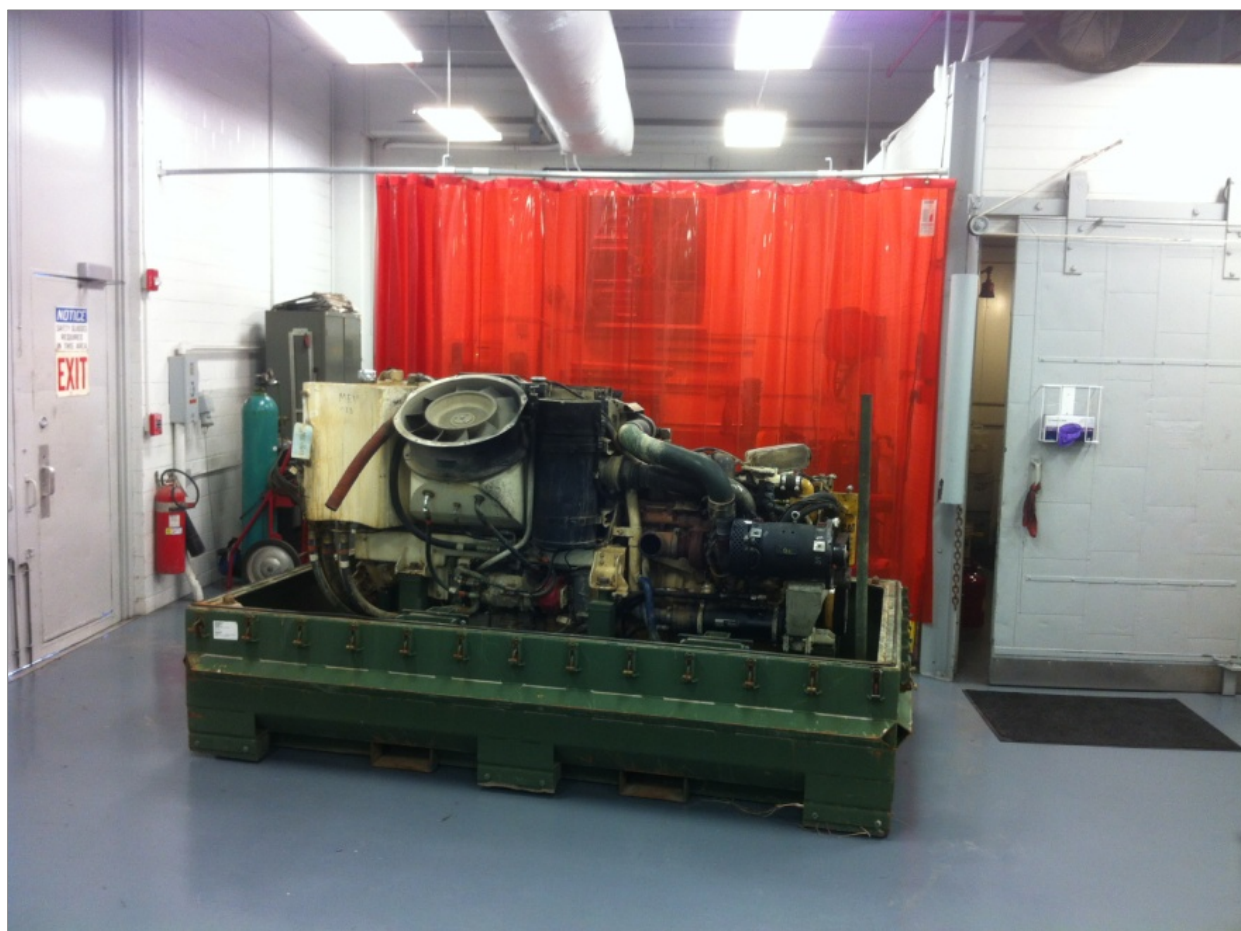


Figure 1. Stryker MEV-013 Powerpack – 1



Figure 2. Stryker MEV-013 Powerpack -2

Once indoors, all ancillary equipment was removed from the powerpack to facilitate removal of the engine. This included all cooling, hydraulic, air conditioning, and electrical control systems. The engine and transmissions were then removed from the main power pack frame assembly, and all removed components were packed back into the crate for disposition.

4.0 RESULTS/DISCUSSION

The engines were evaluated based on metrology procedures to document wear, ratings for internal deposits, and photographs of the “best” and “worst” components removed from the engine. The basis of this data collection was derived from earlier work involving dynamometer engine testing of the CAT C7. This was done so that the data collected from the 3126 engines would have some basis of comparison with previous engine dynamometer evaluations at TFLRF.

4.1 RATINGS

The pistons received full deposits ratings following procedures outlined in the ASTM Deposit Ratings Manual 20 [3]. This included notation of ring sticking, scuffing of the piston rings, piston skirt, and cylinder bore, total piston carbon and lacquer demerits, ratings of the top and intermediate piston ring groove fill, and ratings of the top land heavy and flaked carbon percentages. In addition, the intake and exhaust valves removed from the cylinder heads were also rated for deposits (NOTE: ratings for piston deposits are in demerits, thus a lower numerical value is better, while ratings for valves are in merits, thus a higher numerical value is better).

Table 1 (next page) shows the combined ratings for both the TEST vehicle using SCPL (Stryker IVC-482), and the CONTROL vehicle using MIL-PRF-2104 15W-40 (Stryker MEV-013). At inspection, neither of the engines pistons showed a propensity for ring sticking. Rings at each location for all pistons were free moving in their respective grooves, with no excessive buildup that would inhibit ring movement during engine operation. Stuck or sticking rings can increase engine oil consumption and blow-by during operation, and result in a reduced efficiency and performance of the engine. As all of the rings were found free, both oils tended to show good deposit control.

Table 1. Deposit Ratings Results

		IVC-482 TEST (SCPL)								MEV-013 CONTROL (MIL-PRF-2104)							
Ratings		Cylinder Number						Avg			Cylinder Number						Avg
		1	2	3	4	5	6				1	2	3	4	5	6	
Ring Sticking																	
Ring No.1	No	No	No	No	No	No	No	--			No	No	No	No	No	No	--
Ring No.2	No	No	No	No	No	No	No	--			No	No	No	No	No	No	--
Ring No.3	No	No	No	No	No	No	No	--			No	No	No	No	No	No	--
Scuffing % Area																	
Ring No.1	0	0	0	0	0	0	0	0.00			1	2	1	0	0	0	0.67
Ring No.2	0	0	0	0	0	0	0	0.00			0	0	0	0	0	0	0.00
Ring No.3	0	0	0	0	0	0	0	0.00			0	0	0	0	0	1	0.17
Piston Skirt	0	0	0	0	0	0	0	0.00			2	5	1	2	0	0	1.67
Cylinder Liner, %	0	0	0	0	0	0	0	0.00			1	5	1	1	0	0	1.33
Piston Carbon, Demerits																	
No.1 Groove	52.25	46.25	48.75	35.25	36.75	34.75	42.33				59.50	39.25	32.50	38.00	35.50	27.50	38.71
No.2 Groove	37.00	30.00	25.00	18.50	20.25	17.25	24.67				15.00	22.75	22.50	22.75	20.75	15.25	19.83
No.3 Groove	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cooling Gallery	23.75	23.75	23.75	25.00	25.00	23.75	24.17				23.75	25.00	25.00	25.00	25.00	25.00	24.79
Under Crown	22.50	20.00	25.00	21.25	22.50	18.75	21.67				25.00	25.00	10.00	25.00	25.00	25.00	22.50
No.1 Land	55.00	46.75	62.50	56.50	55.00	58.75	55.75				33.25	40.00	34.00	45.25	43.00	32.50	38.00
No.2 Land	0.00	0.00	5.00	3.75	6.50	0.00	2.54				0.00	0.00	0.00	3.75	0.00	0.00	0.63
No.3 Land	0.00	3.75	0.00	0.00	7.25	1.25	2.04				3.25	1.25	0.00	7.25	12.50	7.25	5.25
No.4 Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00
Piston Lacquer, Demerits																	
No.1 Groove	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00
No.2 Groove	0.00	0.90	0.00	0.80	0.65	0.83	0.53				1.19	0.32	0.30	0.55	0.70	1.18	0.71
No.3 Groove	1.28	1.50	1.28	1.05	1.13	1.10	1.22				0.93	0.92	1.40	1.05	1.19	0.70	1.03
Cooling Gallery	0.23	0.38	0.23	0.00	0.00	0.23	0.18				0.25	0.00	0.00	0.00	0.00	0.00	0.04
Under Crown	0.75	1.50	0.00	1.13	0.75	1.88	1.00				0.00	0.00	5.40	0.00	0.00	0.00	0.90
No.1 Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00
No.2 Land	3.66	2.36	2.07	2.50	1.06	4.88	2.75				4.30	4.89	4.73	2.55	2.78	2.24	3.58
No.3 Land	1.40	1.50	1.40	1.50	2.00	1.95	1.63				1.53	2.75	1.47	0.91	1.02	2.20	1.65
No.4 Land	1.05	1.00	1.00	1.00	1.00	1.00	1.01				0.20	0.20	0.50	0.20	0.50	0.20	0.30
Total, Demerits	198.87	179.64	195.98	168.23	179.84	166.37	181.49				168.15	162.33	137.80	172.26	167.94	139.02	157.91
Miscellaneous																	
Top Groove Fill, %	53	42	53	29	29	27	38.83				56	29	29	29	29	16	31.33
Intermediate Groove Fill, %	29	28	16	7	7	7	15.67				4	9	5	8	9	5	6.67
Top Land Heavy Carbon, %	40	29	50	42	40	45	41.00				11	20	12	27	24	10	17.33
Top Land Flaked Carbon, %	0	0	0	0	0	0	0.00				0	0	0	0	0	0	0.00
Valve Tulip Deposits, Merits																	
Exahust	9.0	8.9	9.0	8.9	8.8	8.9	8.92				8.2	8.0	8.0	8.0	8.0	8.0	8.03
Intake	8.7	8.2	8.8	8.5	8.6	8.6	8.57				7.1	7.2	7.2	7.3	7.1	7.3	7.20

When inspected for scuffing, Stryker IVC-482 (TEST) showed no evidence on the ring surfaces or the piston skirt and bore interface. On the other hand, Stryker MEV-013 (CONTROL) showed several cylinders with one to five percent (1-5%) scuffing on the bore and piston skirt surface. Overall these numbers are relatively low in terms of scuffing that would present major operational problems in an engine, but when comparing to previous testing data for the CAT C7, the presence of scuffing at all does seem unusual. No other CAT C7 engine tests conducted at TFLRF has exhibited scuffing in the past, despite the tested oils viscosity, oil sump temperatures maintained, or the total test duration (up to 630 hours continuous operation at 260 °F oil sump temperatures in one particular case). Although this scuffing could be contributed to the performance of the MIL-PRF-2104, it could also be impacted by engine build parameters (i.e. tighter piston skirt to bore clearance due to piston size, or overall bore diameter variation), any differences in operating conditions, or differences in the previous history between the two vehicles. None of these are completely known, and as a result, we cannot definitively identify the cause of the scuffing in MEV-013 (CONTROL), other than to say it is unusual in nature based on past experience.

For deposits, Stryker MEV-013 (CONTROL) showed an average demerit rating of 157.9 for all six of its pistons. This was less than the average rating of 181.5 seen for Stryker IVC-482 (TEST). Both of these values are higher than that typically seen in previous TFLRF C7 engine dynamometer tests, and suggests a different level of severity in terms of deposit formation between engine dyno operations and the 20k mile RAM-D test. As a result, comparison to previous TFLRF engine testing cannot be made. In an attempt to create a better measure of what is acceptable and not in terms of deposits, results from the 20k mile RAM-D test were instead compared back to the MIL-PRF-2104H [4] specification limits for the ASTM D6684 CAT 1P test (steel piston), which lists piston deposit limits for oil qualification. It is worth noting that the CAT 1P test does use a diesel test fuel ranging from 300-500ppm sulfur. As the Stryker RAM-D test used JP-8 with an unknown sulfur content, there may be bias in the comparison, as fuel composition can have a significant impact on deposit formation. Thus any comparisons should only be taken as an indication in performance, and not true limits. The CAT 1P deposit limits established for a single (1-test) evaluation specify a maximum of 350 demerits, which both vehicles showing ratings well below this value. This suggests that lubricants used in both Stryker

MEV-013 (CONTROL) and IVC-482 (TEST) demonstrate good deposition control. On the other hand, when individual ratings for each piston was compared back to CAT 1P limits for the top groove and top land deposits, Stryker IVC-482 (TEST) showed average results of 42.3 and 55.7 demerits respectively, and Stryker MEV-013 (CONTROL) showed 38.7 and 38.0 demerits respectively. Established limits for the CAT 1P test dictate a maximum allowable 36 demerits for the top groove, and 40 demerits for the top land. This suggests some potential shortcomings in the SCPL used in IVC-482 (TEST) in this particular area. As well, the baseline MIL-PRF-2104 used in Stryker MEV-013 (CONTROL) only met the top groove criteria, but like the SCPL fell short of the top land limits. Since direct comparison to the CAT 1P test is limited, results only give indication of overall performance. Despite this, deposit formation in both Stryker engines was considered low, and well below any level expected to cause operational problems.

Lastly for valve deposits, Stryker IVC-482 (TEST) yielded a rating of 8.9 and 8.6 merits for the exhaust and intake valves respectively, while Stryker MEV-013 (CONTROL) received ratings of 8.0 and 7.2 respectively. This shows the SCPL having a slight advantage over the baseline MIL-PRF-2104 in valve deposit control, but like the piston deposits, both results are considered acceptable. As mentioned previously, without more detailed information of each engines history, or the exact duty cycle experienced by each vehicle, direct deposit comparisons are difficult. Regardless, the engine tear downs showed no major piston or deposition problems from either lubricant that would be expected to cause symptomatic problems in the vehicles.

4.2 METROLOGY

Post test metrology was also completed on select components in an effort to quantify various aspects of the engines post test condition. This included the cylinder bore diameter, piston skirt diameter, piston ring end gap, valve guide and stem diameter, and cam lobe profile variations. Without full pre-test metrology, direct comparisons between the two engines are again difficult, but results are able to be compared to “typical” ranges seen in previous testing, and thus identify any major compatibility problems with the lubricant tested.

Table 2 shows the overall average bore diameter, piston skirt diameter, and the calculated clearance between the two measurements. These measurements gives an indication of overall wear at the piston cylinder interface. (NOTE: The average bore diameter is a numerical average six total measurements of the actual measured bore diameter. These include a transverse and longitudinal measurement at the top, middle, and bottom of the liner bore. Full cylinder bore diameter measurements can be seen in Appendix A). From the results, it appears that both the SCPL and MIL-PRF-2104 oil had acceptable piston/liner wear performance. Although Stryker MEV-013 (CONTROL) shows a minutely smaller piston diameter and a larger overall resulting clearance, both data sets show normal and expected ranges for a used engine, and do not suggest any excessive wear is present. This also confirms that the scuffing identified in ratings section for MEV-013 (CONTROL) was in fact minor, as aggressive wear in the piston and cylinder from scuffing is typically easily identified in post test bore and piston measurements (i.e. larger post test bore to skirt clearances).

Table 2. Post Test Average Bore Diameter, Skirt Diameter, and Clearance [in]

TEST IVC-482	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance		
	1	4.3316	4.3287	0.0029	Average	0.0025
	2	4.3310	4.3286	0.0024		
	3	4.3313	4.3291	0.0022		
	4	4.3311	4.3285	0.0025		
	5	4.3310	4.3286	0.0024		
	6	4.3314	4.3286	0.0028		
					Maximum	0.0029

CONTROL MEV-013	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance		
	1	4.3312	4.3280	0.0032	Average	0.0031
	2	4.3308	4.3279	0.0029		
	3	4.3309	4.3285	0.0024		
	4	4.3312	4.3277	0.0034		
	5	4.3312	4.3279	0.0033		
	6	4.3314	4.3282	0.0032		
					Maximum	0.0034

Table 3 shows the piston ring end gap for both the TEST and CONTROL engines. Results seen here are considered typical, and closely mimic each other despite the differences in the oils evaluated. These results support that both oils are providing adequate protection to this critical interface through a lack of excessive radial ring wear resulting in increased end gap.

Table 3. Post Test Piston Ring End Gap [in]

TEST IVC-482			CONTROL MEV-013		
Cylinder	Ring No.	Post	Cylinder	Ring No.	Post
1	1	0.010	1	1	0.011
	2	0.032		2	0.034
	3	0.020		3	0.020
2	1	0.010	2	1	0.008
	2	0.035		2	0.035
	3	0.024		3	0.021
3	1	0.010	3	1	0.011
	2	0.030		2	0.035
	3	0.024		3	0.021
4	1	0.010	4	1	0.013
	2	0.031		2	0.036
	3	0.024		3	0.022
5	1	0.010	5	1	0.015
	2	0.033		2	0.033
	3	0.022		3	0.022
6	1	0.010	6	1	0.010
	2	0.028		2	0.033
	3	0.023		3	0.021

Average (Ring 1)	0.010	Average (Ring 1)	0.011
Average (Ring 2)	0.032	Average (Ring 2)	0.034
Average (Ring 3)	0.023	Average (Ring 3)	0.021
Max (Ring 1)	0.010	Max (Ring 1)	0.015
Max (Ring 2)	0.035	Max (Ring 2)	0.036
Max (Ring 3)	0.024	Max (Ring 3)	0.022

In addition to the piston and cylinder metrology, the cylinder heads were also disassembled to assess the condition of the valve train. Table 4 shows the resulting valve stem to guide clearance for the intake and exhaust valves. (Note: Full detailed measurements of the valve stem outside diameter (OD) and valve guide inside diameter (ID) are included in a table in Appendix A). From these measurements we can see similar average clearances for both TEST and CONTROL engines, all of which are considered normal ranges for a used engine. There does appear to be one outlier in the data collected from Stryker MEV-013 (CONTROL). Clearance for its number three intake valve is substantially larger than all the other clearances measured for both engines. Review of the detailed measurement data (shown in Appendix A) shows a guide diameter of 0.3199" for this location, which is approximately 0.020" larger than all other measurements taken. This larger ID measurement appears to be the cause of larger clearance, and it is not directly attributed to the oil evaluated. If it was a result of the tested lubricant, other guide measurements would have been expected to show similar trends.

Table 4. Post Test Valve Stem to Guide Clearance [in]

Cylinder	TEST IVC-482		CONTROL MEV-013	
	INTAKE	EXHAUST	INTAKE	EXHAUST
1	0.0030	0.0035	0.0029	0.0028
2	0.0031	0.0033	0.0029	0.0029
3	0.0031	0.0036	0.0053	0.0031
4	0.0024	0.0027	0.0029	0.0033
5	0.0030	0.0029	0.0029	0.0031
6	0.0027	0.0030	0.0030	0.0030
Average	0.0029	0.0032	0.0033	0.0030
Maximum	0.0031	0.0036	0.0053	0.0033

Lastly each camshaft was measured to determine the overall profile variation across the cam lobes. This gives an indication of overall camshaft wear. Table 5 (below) shows the lobe by lobe waviness parameter, which is a measurement between the highest and lowest point across the worn area of the peak lobe profile. Results for both Stryker MEV-013 (CONTROL) and Stryker IVC-482 (TEST) are similar overall. In effect, there was very little wear seen on the camshafts when removed from the engine, and this again shows that both oils tested provided adequate protection of the valve train.

Table 5. Post Test Cam Lobe Variation [μm]

		TEST IVC-482	CONTROL MEV-013
Cylinder	Lobe	μm	μm
1	Intake	1.46	1.28
	Exhaust	1.43	1.36
2	Intake	1.23	1.15
	Exhaust	1.46	1.22
3	Intake	1.29	1.21
	Exhaust	0.93	1.33
4	Intake	1.25	1.39
	Exhaust	1.14	1.36
5	Intake	0.86	1.50
	Exhaust	1.31	1.41
6	Intake	0.98	1.18
	Exhaust	0.96	1.50

4.3 PHOTOGRAPHS

Photographs were taken of “best” and “worst” components, with selection of each being based on their total deposit demerits rating. This was to help document the visual inspection portion of the engine teardown, and visually convey the end of test condition between the two engines.

Figure 3 and Figure 4 below shows the best and worst bores of each engine. In these photos you can see the scuffing tendency for the baseline MIL-PRF-2104 oil used in Stryker MEV-013 (CONTROL). All bore photos were shot on the thrust side of the cylinder bore.

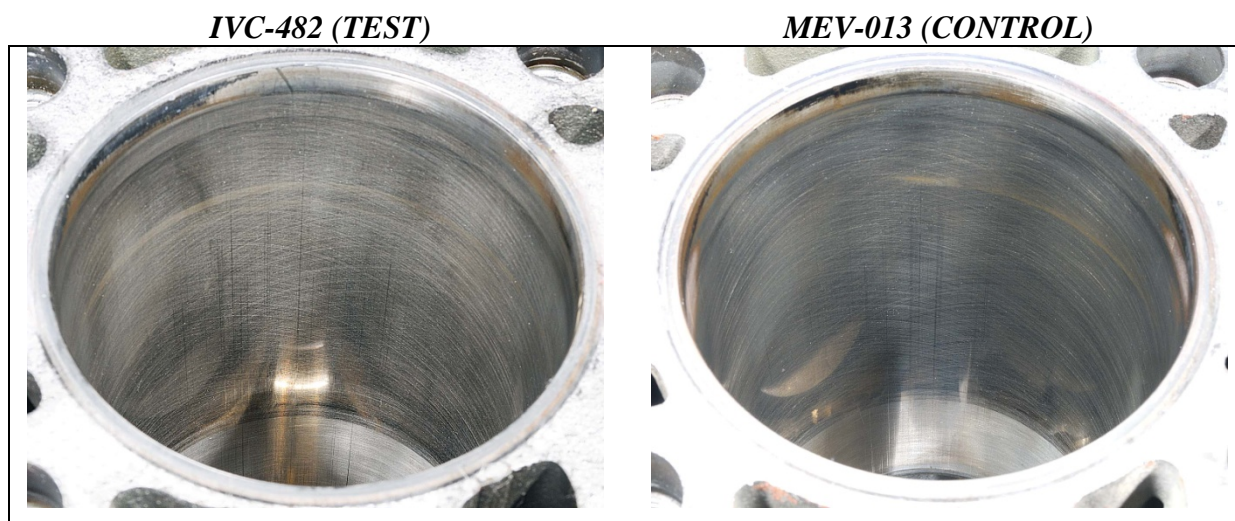


Figure 3. Cylinder Bore “Best”, TEST: #5, CONTROL: #5

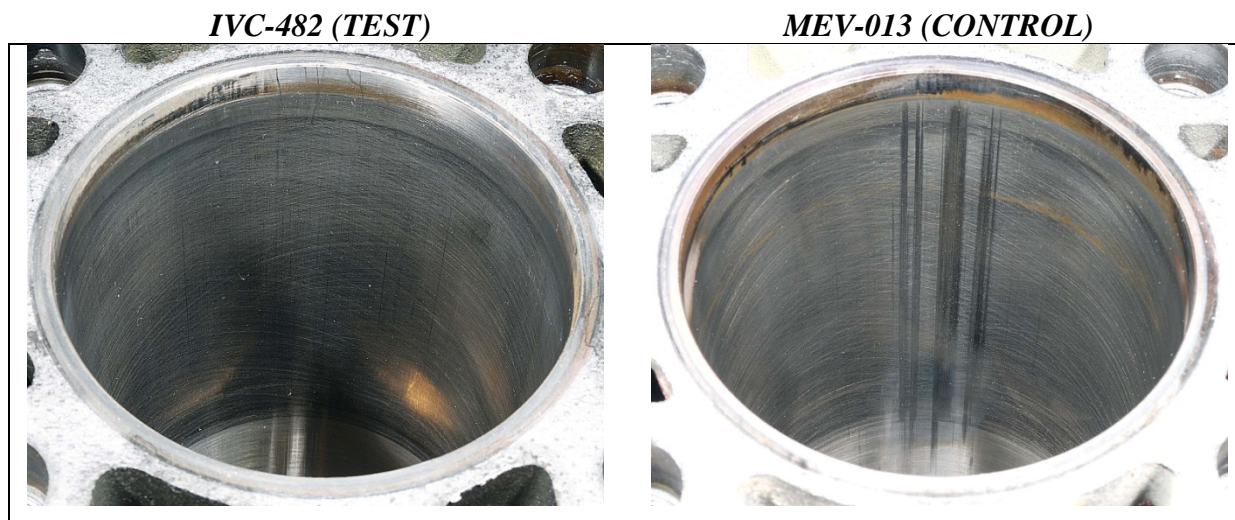


Figure 4. Cylinder Bore “Worst”, TEST: #5, CONTROL: #2

Figure 5 and Figure 6 show the best and worst piston skirts from each engine. Like that seen in the bore photos, the pistons from Stryker MEV-013 (CONTROL) do show more markings consistent with the identified scuffing. Like the bore photos, all piston photos shown are the thrust side of the piston skirt, which is typically the highest wear area. Deposit formation appears similar in each photo shown. (Additional photos of the anti-thrust side of the piston skirt, and shots of the piston crown and under crown can be seen in Appendix B).

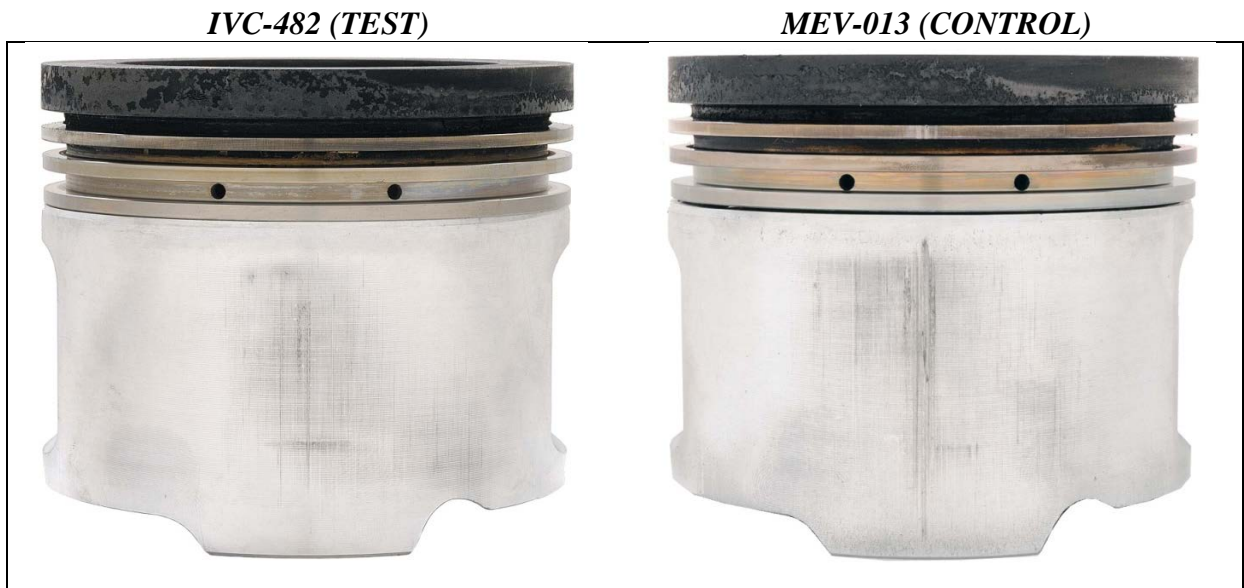


Figure 5. Thrust Side, Piston Skirt “Best”, TEST: #6, CONTROL: #3



Figure 6. Thrust Side, Piston Skirt “Worst”, TEST: #1, CONTROL: #4

Figure 7 shows the best exhaust and intake valve for the TEST and CONTROL engine. As previously mentioned, valves are rated on a merits system, thus a higher score is better. The valves chosen for best and worst representation are the highest and lowest sum total merits for both the intake and exhaust valves from the ratings. Deposit formation here is primarily visible on the back side of the intake valve tulip (the larger valve, shown right in each photo). The intake valve for IVC-482 is almost completely clean, while the intake of MEV-013 shows light deposition.

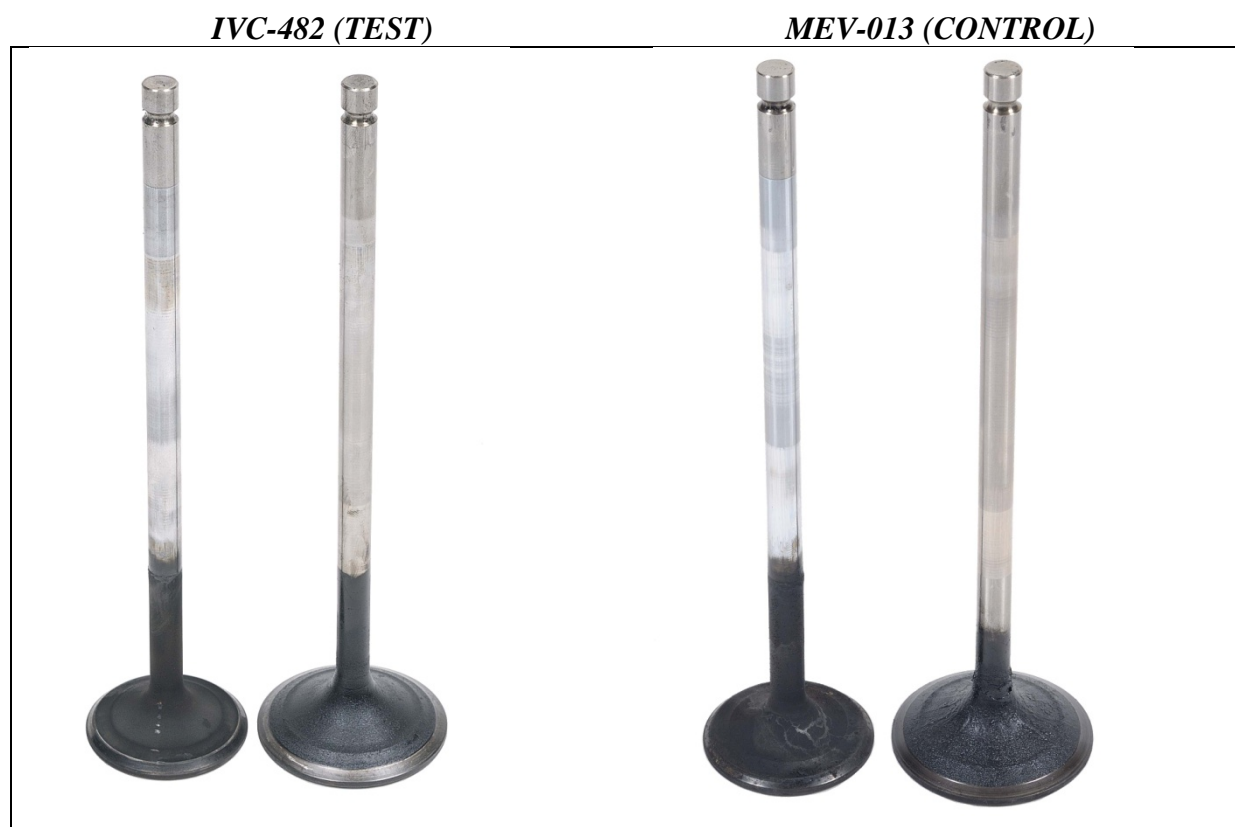


Figure 7. Exhaust and Intake Valves “BEST”, TEST: #3, CONTROL: #1

Figure 8 shows the worst pair of exhaust and intake valves. Note the increased accumulation of deposits on the back side of each intake valve tulips compared to the valves shown in the previous photos.

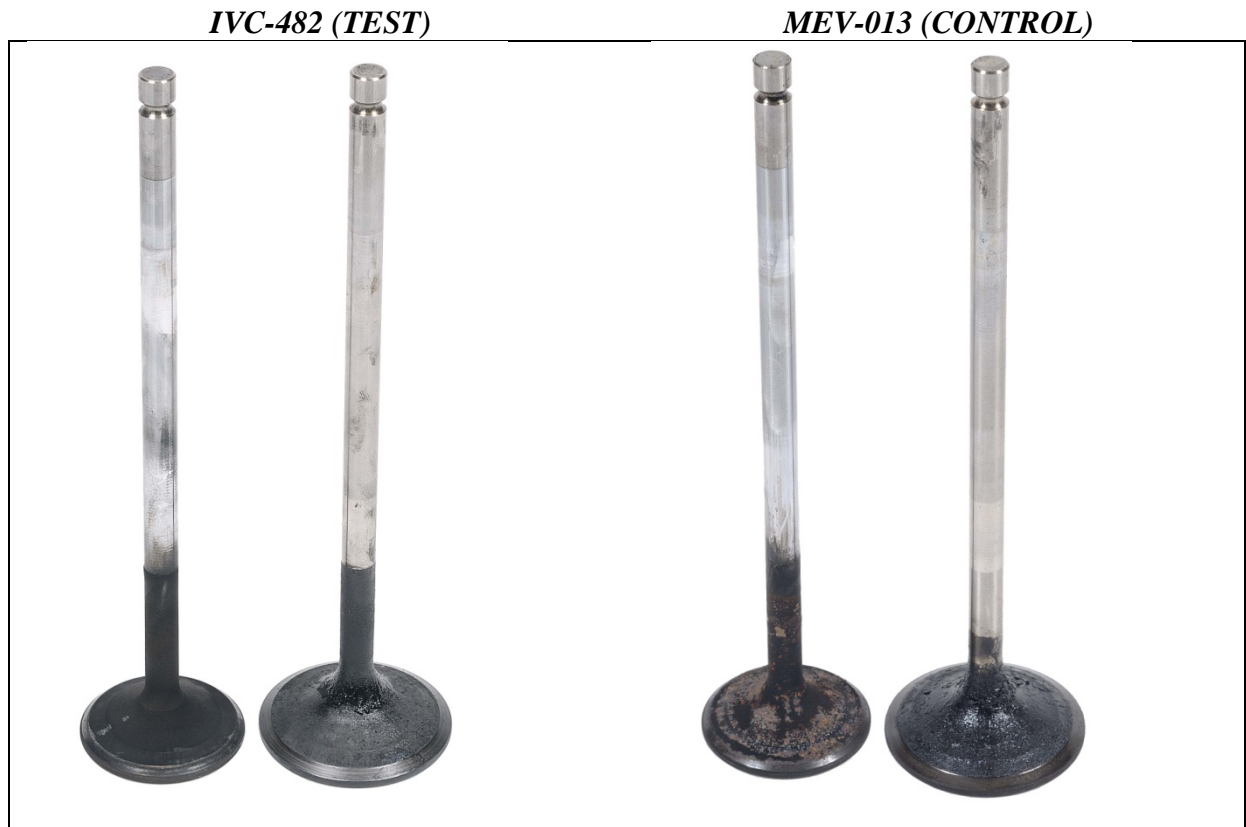


Figure 8. Exhaust and Intake Valves “WORST”, TEST: #2, CONTROL: #5

Figure 9 shows the connecting rod bearings removed from each engine. Engine bearings typically are a good indicator of the oils performance and condition during testing, especially the connecting rod bearings which experience high loading from combustion. The orientation of the bearings shown are upper shells on the left, lower on the right, cylinder number one through six top to bottom. An increased amount of distress is seen on outer edges of the shells from Stryker IVC-482 (TEST), while only heavy polish is noted on Stryker MEV-013 (CONTROL). This is undesirable, and could potentially be attributed to the lower viscosity of the SCPL, or differences in the initial build of the engine. Without more information, the root cause is unknown. Despite this, bearings from IVC-482 still show good overall condition, and do not appear to be of concern for immediate engine issues. Review of used oil analysis from samples taken during testing is recommended to determine if any significant accumulation differences in wear metals typical of bearing wear exist.

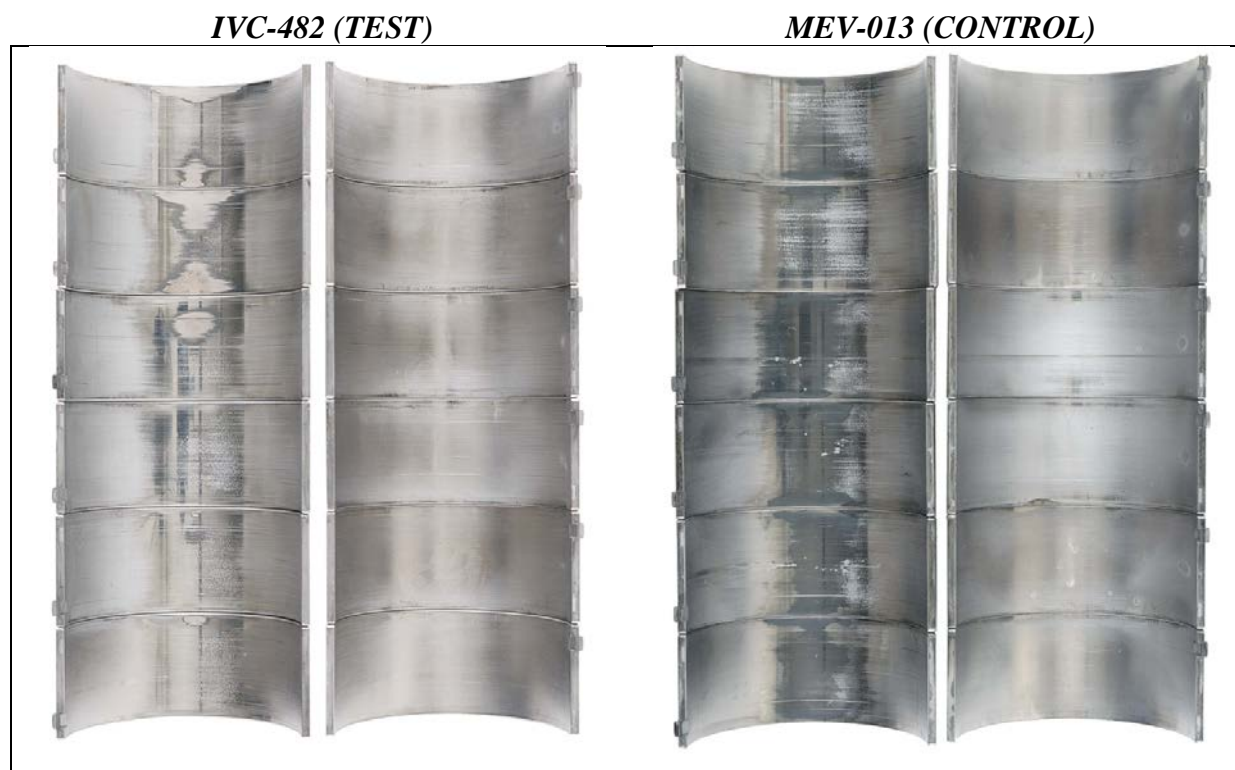


Figure 9. Connecting Rod Bearings (ALL)

Figure 10 shows the crankshaft main bearings for the TEST and CONTROL vehicles. Both sets of bearings removed from the engine showed similar wear patterns, and no signs of heavy distress or wear. Overall main bearing condition was found to be better than the connecting rod bearings.

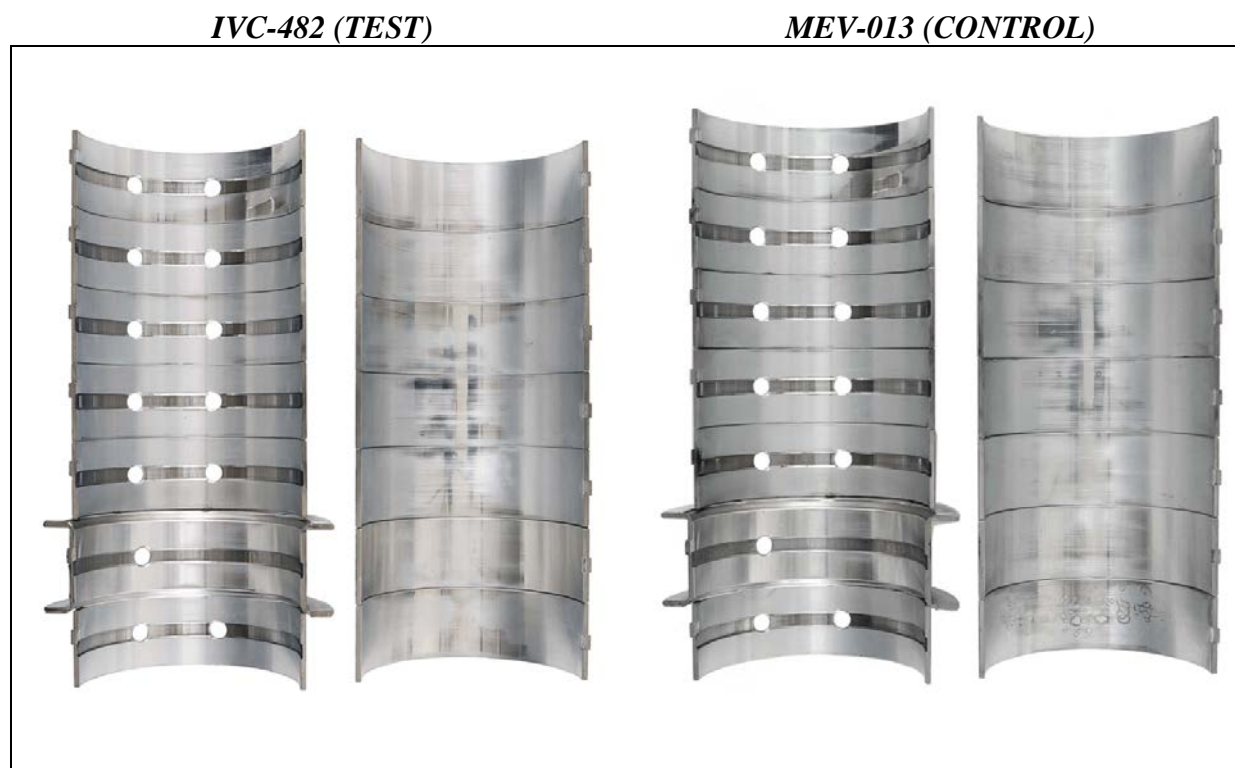


Figure 10. Crankshaft Main Bearings (ALL)

Additional photographs of the engines pistons, thrust bearings, and piston rings can be found in Appendix B. These photos were not included in the main discussion, as visually they show little difference between the two tested oils, and in general are less of a tell tale sign of the oils performance (apart from major oil or engine failure). As a result, they were captured and included in the appendix for review, but not brought up in the main report for additional discussion.

5.0 CONCLUSIONS

In conclusion, the two engines removed from Stryker IVC-482 (TEST) and MEV-013 (CONTROL) were disassembled and inspected, and were found to be in similar overall condition in respect to metrology, ratings, and a visual inspection. The condition of both engines were considered typical for a used engine in good working order.

In the metrology section, no major wear was identified in either engine. All post test metrology results were within what would be considered normal or expected ranges for used engines in good working order, and similar overall to results seen in previous CAT C7 engine dynamometer testing completed at TFLRF. Similarly, deposition control for the pistons and valves was found to be acceptable in both engines. The MIL-PRF-2104 used by MEV-013 did show less total accumulation of deposits (i.e. lower ratings) than the SCPL used in IVC-482, but the SCPL showed an advantage in valve deposit control over MIL-PRF-2104. Both oil's performance was considered sufficient, and end of test deposits present in both engines at tear down would not suggest any significant formulation problems with either oil.

After the completion of the tear down and inspection, and review of all test results, it is the opinion of TFLRF staff that the SCPL candidate provided comparable performance to that from the baseline MIL-PRF-2104 in the Stryker CAT 3126 engines. It is expected that the SCPL can be used as a drop in replacement for the MIL-PRF-2104 without negatively impacting the overall performance of the vehicle and the resulting engine protection.

6.0 REFERENCES

1. Brandt, A.C., Frame, E.A., Hansen, G.A., Warden, R.W., “*Single Common Powertrain Lubricant Development*,” Interim Report TFLRF No. 418, ADA577551, January 2012.
2. Brandt, A.C., Frame, E.A., Hansen, G.A., Warden, R.W., “*Single Common Powertrain Lubricant Development (Part 2)*,” Draft Interim Report TFLRF No. 442, June 2013.
3. ASTM Deposit Rating Manual 20 (Formerly CRC Manual 20), ASTM International, West Conshohocken, PA, www.astm.org.
4. Military Specification MIL-PRF-2104H, Lubricating Oil, Internal Combustion Engine, Combat/Tactical Service, revision H, 12 July 2004

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APPENDIX A.
Detailed Metrology Tables

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Table A-1 and Table A-2 shows the post test cylinder bore inside diameter, average bore diameter, and out of round measurements. The bore was measured in the longitudinal (parallel with crank) and transverse (perpendicular to the crank) direction at three locations in the bore.

Table A-1. Stryker IVC-482 (TEST) Post Test Cylinder Bore Diameter [in]

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD)	Out of
1	Top	4.3311	4.3318		0.0007
	Middle	4.3312	4.3320	4.3316	0.0008
	Bottom	4.3320	4.3319		0.0001
	Taper	0.0009	0.0002		
2	Top	4.3309	4.3322		0.0013
	Middle	4.3307	4.3330	4.3310	0.0023
	Bottom	4.3313	4.3324		0.0011
	Taper	0.0006	0.0008		
3	Top	4.3312	4.3320		0.0008
	Middle	4.3310	4.3328	4.3313	0.0018
	Bottom	4.3315	4.3322		0.0007
	Taper	0.0005	0.0008		
4	Top	4.3310	4.3317		0.0007
	Middle	4.3308	4.3325	4.3311	0.0017
	Bottom	4.3313	4.3320		0.0007
	Taper	0.0005	0.0008		
5	Top	4.3308	4.3318		0.0010
	Middle	4.3307	4.3326	4.3310	0.0019
	Bottom	4.3313	4.3320		0.0007
	Taper	0.0006	0.0008		
6	Top	4.3311	4.3316		0.0005
	Middle	4.3312	4.3320	4.3314	0.0008
	Bottom	4.3316	4.3317		0.0001
	Taper	0.0005	0.0004		

Table A-2. Stryker MEV-013 (CONTROL) Post Test Cylinder Bore Diameter [in]

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD)	Out of
1	Top	4.3309	4.3312		0.0003
	Middle	4.3310	4.3318	4.3312	0.0008
	Bottom	4.3314	4.3315		0.0001
	Taper	0.0005	0.0006		
2	Top	4.3307	4.3317		0.0010
	Middle	4.3306	4.3325	4.3308	0.0019
	Bottom	4.3310	4.3320		0.0010
	Taper	0.0004	0.0008		
3	Top	4.3309	4.3316		0.0007
	Middle	4.3307	4.3326	4.3309	0.0019
	Bottom	4.3311	4.3320		0.0009
	Taper	0.0004	0.0010		
4	Top	4.3311	4.3317		0.0006
	Middle	4.3309	4.3325	4.3312	0.0016
	Bottom	4.3314	4.3320		0.0006
	Taper	0.0005	0.0008		
5	Top	4.3311	4.3319		0.0008
	Middle	4.3309	4.3327	4.3312	0.0018
	Bottom	4.3314	4.3321		0.0007
	Taper	0.0005	0.0008		
6	Top	4.3313	4.3315		0.0002
	Middle	4.3310	4.3318	4.3314	0.0008
	Bottom	4.3318	4.3317		0.0001
	Taper	0.0008	0.0003		

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Table A-3 and Table A-4 show the valve guide inside diameter and the valve stem outside diameter that the valve stem to guide clearance values shown in the metrology section were calculated from.

Table A-3. Stryker IVC-482 (TEST) Post Test Valve Train Measurements [in]

Cylinder	VALVE GUIDE DIAMETER		VALVE STEM DIAMETER		CLEARANCE	
	INTAKE	EXHAUST	INTAKE	EXHAUST	INTAKE	EXHAUST
1	0.3177	0.3178	0.3147	0.3143	0.0030	0.0035
2	0.3179	0.3179	0.3148	0.3146	0.0031	0.0033
3	0.3178	0.3179	0.3147	0.3143	0.0031	0.0036
4	0.3172	0.3172	0.3148	0.3145	0.0024	0.0027
5	0.3178	0.3174	0.3148	0.3145	0.0030	0.0029
6	0.3176	0.3176	0.3149	0.3146	0.0027	0.0030

Table A-4. Stryker MEV-013 (CONTROL) Post Test Valve Train Measurements [in]

Cylinder	VALVE GUIDE DIAMETER		VALVE STEM DIAMETER		CLEARANCE	
	INTAKE	EXHAUST	INTAKE	EXHAUST	INTAKE	EXHAUST
1	0.3175	0.3174	0.3146	0.3146	0.0029	0.0028
2	0.3175	0.3194	0.3146	0.3145	0.0029	0.0049
3	0.3199	0.3175	0.3146	0.3144	0.0053	0.0031
4	0.3176	0.3176	0.3147	0.3143	0.0029	0.0033
5	0.3175	0.3175	0.3146	0.3144	0.0029	0.0031
6	0.3176	0.3174	0.3146	0.3144	0.0030	0.0030

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APPENDIX B.
Photographs

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The following are additional photographs taken of internal components after the internal inspection. These photographs, unlike those shown in the main report, show less overall distinction between the TEST and CONTROL vehicles, thus were not included in the main discussion. Photos and captions are included below.

Figure B-1 Figure B-2 below show the best and worst piston crowns. As with the previous photos, best and worst selection was based on the total demerits for each piston. Apart from coloration, both vehicles showed similar condition.



Figure B-1. Piston Crown, “Best”, TEST: #6, CONTROL: #3

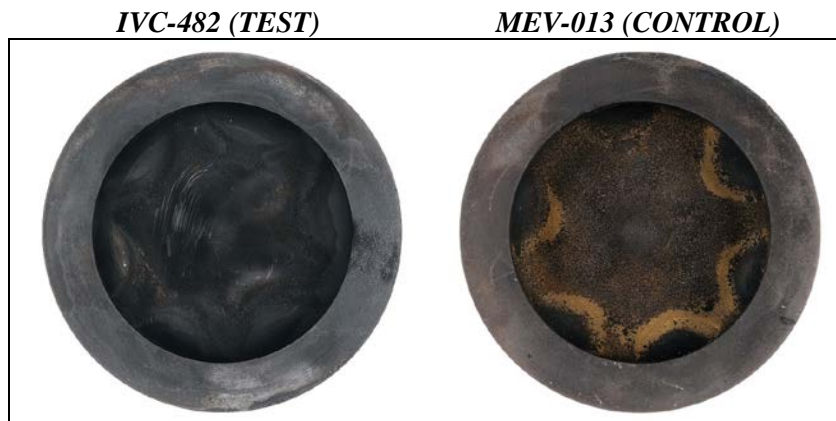


Figure B-2. Piston Crown, “Worst”, TEST: #1, CONTROL: #4

Figure B-3 and Figure B-4 show the best and worst anti-thrust side of the piston skirt. The scuffing tendency seen by MEV-013 is not apparent on the anti-thrust side, as it is the more lightly loaded surface of the piston compared to the thrust side.

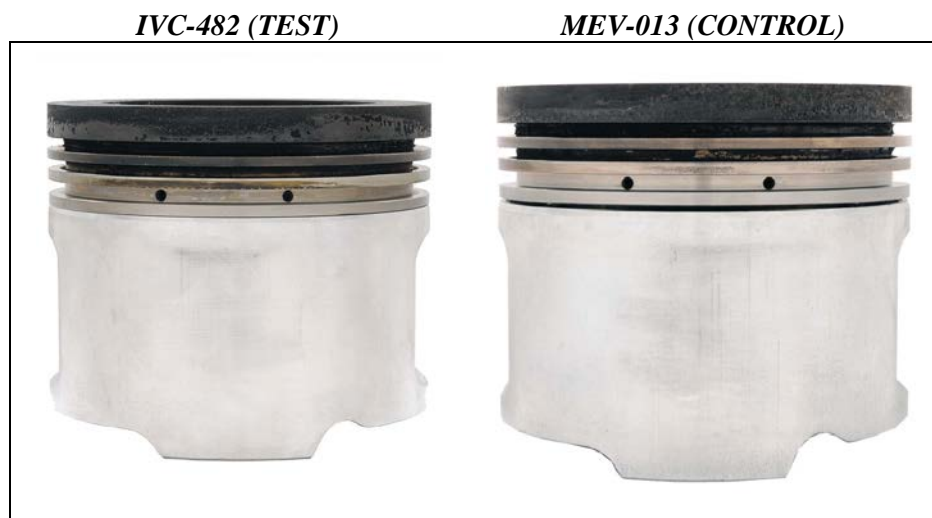


Figure B-3. Piston Skirt Anti-Thrust, “Best”, TEST: #6, CONTROL: #3



Figure B-4. Piston Skirt Anti-Thrust, “Worst”, TEST: #1, CONTROL: #4

Figure B-5 and Figure B-6 show the best and worst under crown. Conditions of each are similar, with the IVC-482 under crowns appearing to show a slightly higher deposition level, consistent with the overall piston deposits ratings reported.

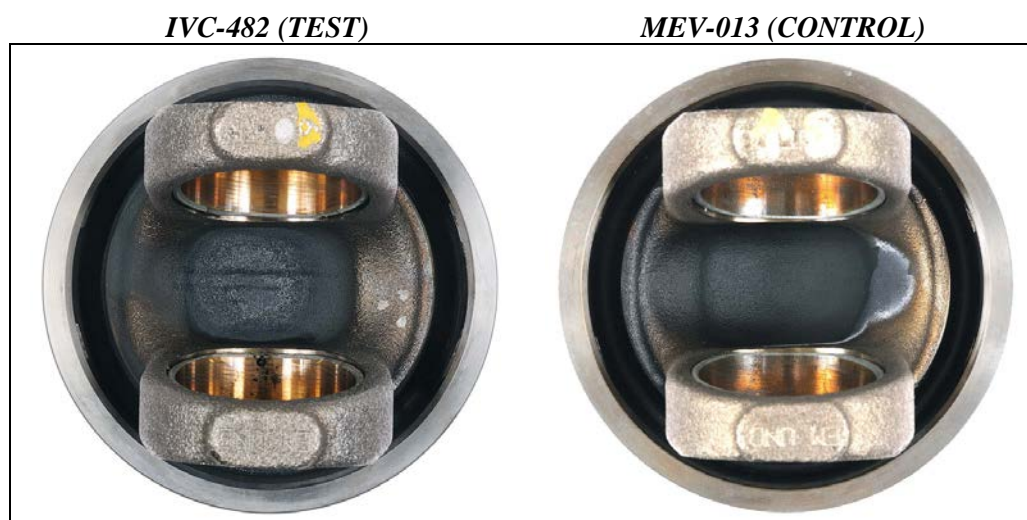


Figure B-5. Piston Under Crown, “Best”, TEST: #6, CONTROL: #3

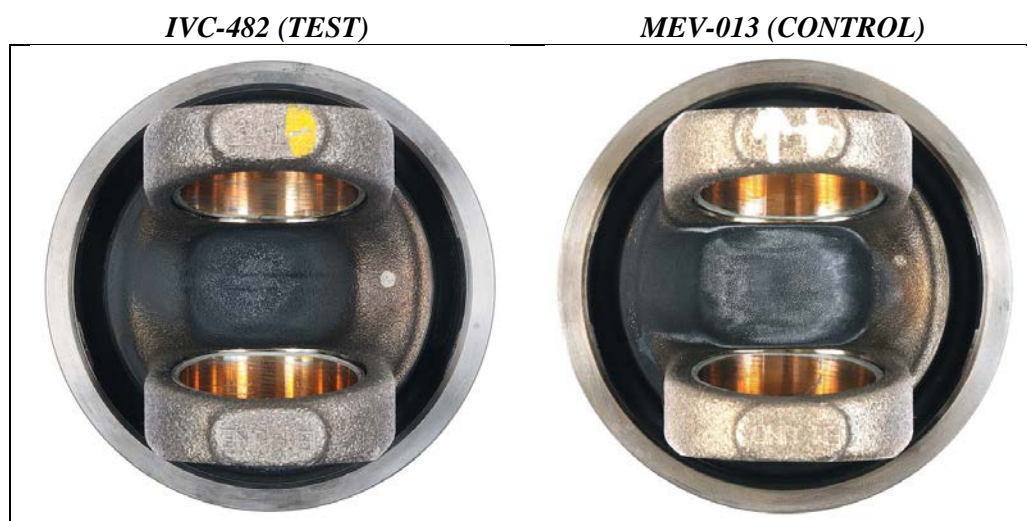


Figure B-6. Piston Under Crown, “Worst”, TEST: #1, CONTROL: #4

Figure B-7 and Figure B-8 show the piston rings. Condition of each were found to be very similar upon removal, with no major signs of distress or wear on each.

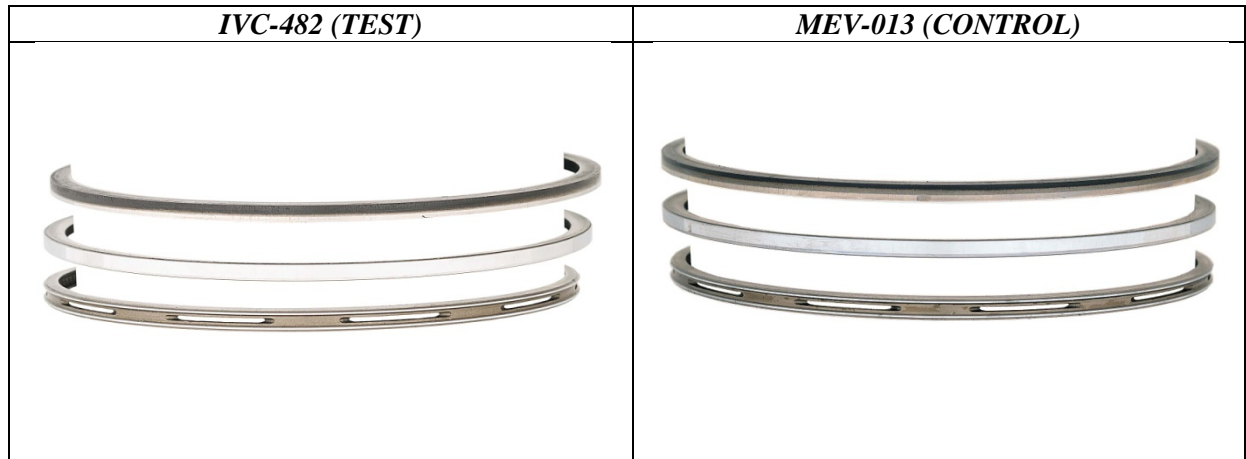


Figure B-7. Piston Ring Pack, “Best”, Test: #6, Control: #3



Figure B-8. Piston Ring Pack, “Worst”, Test: #1, Control: #4

Figure B-9 and Figure B-10 show the back side (facing the flywheel) of the crankshaft thrust bearing surface. This is the area of highest wear for the thrust bearing. Both removed bearings were found to be in good condition overall.

IVC-482 (TEST)



Figure B-9. Thrust Bearing Back, TEST

MEV-013 (CONTROL)



Figure B-10. Thrust Bearing Back, CONTROL

Figure B-11 and Figure B-12 show the front side of the crankshaft thrust bearing surface, which should see less wear typically than the back side. Like the back surfaces, both removed bearings were found to be in good condition overall.

IVC-482 (TEST)



Figure B-11. Thrust Bearing Front, TEST

MEV-013 (CONTROL)



Figure B-12. Thrust Bearing Front, CONTROL